OPTICAL FIBER-BASED SENSING OF STRAIN AND TEMPERATURE AT HIGH TEMPERATURE

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INTRODUCTION

In-line intensity-based and Fabry-Perot silica optical fiber sensors have been developed to measure strain and temperature at temperatures up to 1500°F. The intensity-based sensor is an air gap splice in which the gap spacing changes as the length of the sensor housing changes. Two silica multimode optical fibers are placed in a hollow silica tube so their ends are separated by an initial gap spacing. As the sensor is strained, the gap spacing varies, resulting in a predictable change in output intensity. The Fabry-Perot sensor uses both single-mode and multimode fibers which are axially aligned inside a similar hollow core fiber. The four percent reflections which occur at both the glass-air interface at the end of the input single-mode fiber and at the air-glass interface at the surface of the multimode fiber differ in phase by an amount proportional to the separation between the two fiber ends. As the sensor is strained, the separation distance between these fiber ends changes, and the output signal intensity varies due to the interference between the reflected signals.

Optical fiber sensors have been applied to the characterization of materials and structures since 1979 [1]. Much of this work has focused on the implementation of fiber-based devices which in their operation and performance are similar to those of conventional sensors such as strain gages, piezoelectric ultrasonic transducers, and accelerometers [2, 3]. Fiber sensors operate on the principle that an external phenomenon such as pressure, strain or temperature modulates one of the properties of the light which propagates in the fiber sensor system, including optical intensity, phase, polarization, wavelength, and modal structure. Using an analytical model of the modulation as a basis, the modulation of the optical signal at the output of the sensor may be interpreted in terms of the external phenomenon. During the past ten years, such fiber sensor systems, either embedded within materials or attached to their surfaces, have been used to characterize strain, temperature, vibration, and ultrasonic waves in materials, and to locate and characterize impact damage and acoustic emission events [4].

This paper describes measurements of temperature-induced deformation obtained using both intensity-based air-gap devices and in-line silica fiber Fabry-Perot interferometers. Section 2 describes the sensors; Section 3 discusses the results of experimental measurements and their possible implications for the quantitative nondestructive evaluation of materials.

OPTICAL FIBER SENSOR DESIGN

In-Line Intensity-Based Air-Gap Sensor

An in-line extrinsic intensity-based fiber sensor was fabricated as shown in Figure 1. Here, two 100/140 μm-diamter multimode silica fibers are held aligned in a hollow core silica fiber with a 143 μm inner diameter. Light from an infrared laser source exits the end of the input fiber in the tube and partially couples across a separation gap of length s into the facing end of the output fiber and is transmitted to an optical detector. The change in the optical coupling loss across the gap varies versus s as

$$\text{Loss (dB)} = 10 \log_{10}\{(d/2)/[(d/2) + s \tan(\sin^{-1}(NA/n_o))]\}^2, \qquad (1)$$

where d is the diameter of the fiber, NA is the numerical aperture, given by $(n_1^2 - n_2^2)^{1/2}$, n_1 is the index of refraction of the fiber core, n_2 is the index of the cladding, and n_o is the index of refraction of the material in the gap, usually air. A corresponding experimental measurement of the output optical power versus separation distance is shown in Figure 2.

In-Line Fabry-Perot Sensor

The Fabry-Perot sensor is shown in Figure 3 [5]. The sensor consists of an input/output single mode fiber at the left of the sensor housing and a target glass fiber at the right. The cleaved ends of both fibers are held in axial alignment in a cylindrical hollow core silica fiber tube and are slightly separated. The inner diameter of the tube is dimensioned during manufacturing to be slightly larger than the

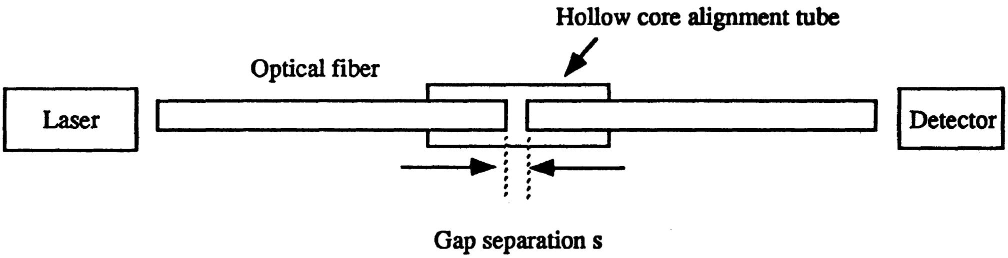

Figure 1. Intensity-based fiber sensor geometry.

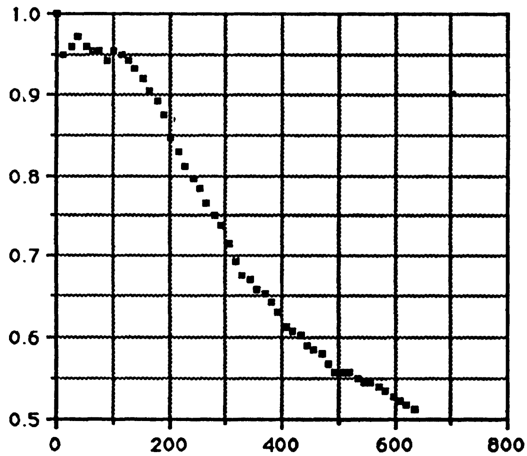

Figure 2. Optical power versus separation distance.

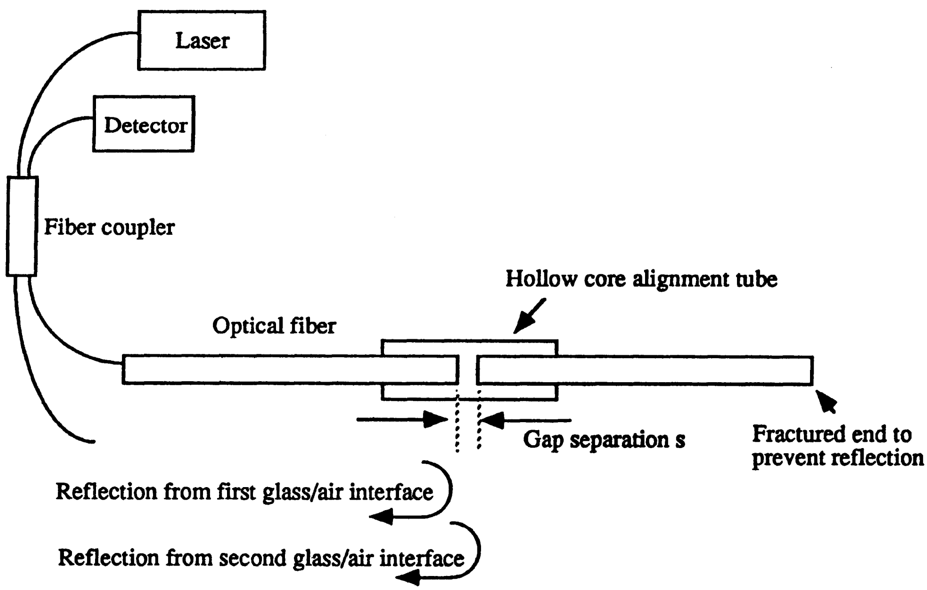

Figure 3. Extrinsic Fabry-Perot sensor geometry.

outer diameters of the claddings of the two fibers. This allows for ease of assembly and yields an acceptable fiber end-to-fiber end alignment.

Light from a laser source is coupled into single-mode silica fiber which is connected to the input end of the sensor through a 3 dB 2x2 fused biconical tapered single mode coupler. At the end of the input fiber inside the tube, part of the light from the source is reflected, and part exits the fiber and reflects off the cleaved, uncoated surface of the facing target fiber. The intensity of the optical signal coupled back into the input fiber is determined by summing the electromagnetic field contributions from these two reflections. The phase difference ϕ between the return signal components due to the path difference is given by

$$\phi = (2\pi/\lambda)2s, \tag{2}$$

where λ is the wavelength of light. As the separation distance varies, the intensity of the interference optical signal coupled back into the input fiber is thus modulated. The output intensity signal is directed back through the same 2x2 coupler to an optical detector, and the amplitude of the detected signal is expressed in terms of the surface displacement as

$$I_{det} \propto 1 + 2[Ta/(a + 2s\tan(\sin^{-1}NA))]\cos\phi + [Ta/(a + 2s\tan(\sin^{-1}NA))]^2, \tag{3}$$

where a is the radius of the fiber core, and T is the transmission coefficient at the air-glass interface, here approximately 96%.

Displacements which are large compared to an optical wavelength result in the successive detection of a large number of intensity maxima and minima characteristic of the interference phenomenon, and total displacement may be determined by counting the number of fringes received, where each fringe corresponds to one maxima-minima-maxima period.

EXPERIMENTAL MEASUREMENTS

The attachment of both of the sensors to the specimen is important to the interpretation of the output signals of the sensor systems [6]. Attachment between the fibers outside the ends of the hollow core tubing and the specimen was made at two locations using ceramic-based adhesive rated for use above 900°C. The separation between the two locations of adhesive defines the gage length of the sensor element in each case, here approximately 1.0 cm for the Fabry-Perot sensor and 8.0 cm for the intensity-based sensor. Because to a first order the sensor system only gives an indication of the displacement between these two locations which define the geometrical axis of the sensor, the output signal may be interpreted as the projection of the differential u, v, and w displacements of those locations, in the Cartesian x, y and z coordinate directions,

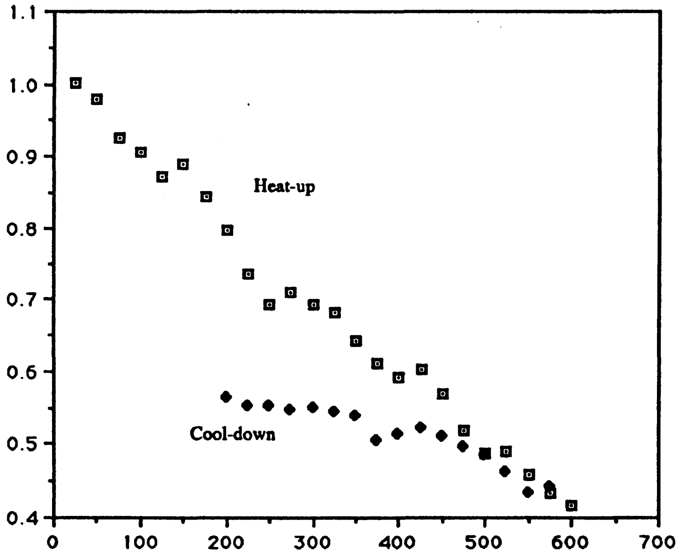

Figure 4. Normalized output versus temperature (°C).

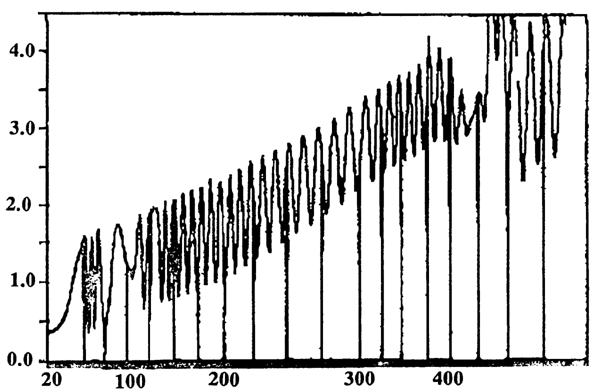

Figure 5. Fabry-Perot sensor output (volts) versus temperature (°C).

respectively, on the generalized axis of the sensor. A more detailed analysis would consider the anisotropic properties of both the specimen, the sensor materials and the attachment materials, as well as the anisotropic thermal expansion coefficients of all of the individual sensor components.

Both sensors were attached to a mullite ceramic specimen which was subsequently heated. The heat caused a deformation of the specimen which in turn induced strain in the sensor housings. Output signals from the two in-line sensors, shown over a range of approximately room temperature to 500°C, are given in Figures 4 and 5.

RESULTS AND DISCUSSION

Figure 4 indicates that as a function of increasing and then decreasing temperature some hysteresis in the output of the air-gap intensity-based sensor is observed, perhaps as suggested by recent time domain-based measurements of fiber index properties around 600°C [7]. The noise-limited minimum detectable displacement of this experimental system is on the order of 1 micron.

Figure 5 shows the multi-fringe output of the Fabry-Perot sensors over the same temperature range; here the minimum detectable elongation is on the order of 1-10 nm. The upward baseline drift of the sensor output is attributed to the intensity effect described above. It is noted and emphasized that the approach reported is extrinsic in nature and not like the Fabry-Perot approach reported in [8]. Here, we have specifically used an extrinsic geometry to avoid the thermal expansion cycling and irreversible fiber deformation effects which have been observed to influence the fibers used in-line Fabry-Perot sensors. Recent work has led to the development of a phase quadrature method which allows the unambiguous determination of the direction of strain, as well as the amplitude [9], and the detection of strain induced by cracks in materials [10].

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